An Economical Means for Accurate Azimuthal Alignment of Polarization Optics

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ABSTRACT

For many applications involving polarized light, it is important that the azimuthal angle of a polarization optic (i.e. polarizer, retarder, etc…) be accurately aligned to a physical datum or to an eigenaxis of another polarization optic. A simple opto-mechanical tool for azimuthal alignment can be used to perform accurate alignments and consists of two "rotatable" mounts. One mount holds a polarizer, while the other holds a half-wave retarder. The method of swings is used to aid in the azimuthal alignment of the polarization optic and is illustrated using the Poincaré Sphere. Additionally, imperfections in polarization optics are discussed.

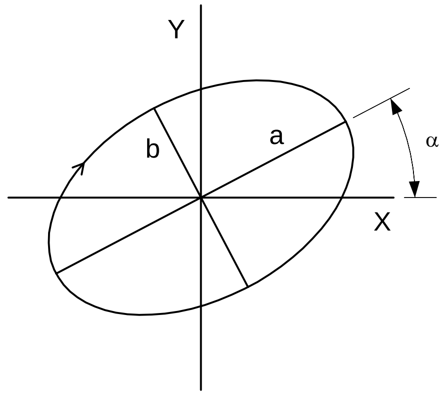
Keywords: alignment, polarization, optic, polarizer, azimuthal, kinematic, swings, waveplate

1. INTRODUCTION

1.1. Polarized Light Basics

Polarized light can be divided into three different states: linear, elliptical, and circular. For monochromatic light, these three states can be represented using their electric field amplitudes and a phase lag term. The electric field amplitudes are broken down into their x and y components, which are aligned to a convenient reference frame. The phase lag term describes the phase relationship between the x and y components. A phase lag of ±90˚ describes circularly polarized light, while a phase lag of 0˚ describes linearly polarized light. Other phase lags between -180˚ and +180˚ describe elliptically polarized light. The ellipticity, ε, is defined as the ratio of the minor axis, b, over the major axis, a, and α is the angle of the major axis from the horizontal, as shown in Figure 1. All non-linear states also have a handedness. A snapshot of a right-handed circular wavetrain resembles the helix of a right-handed screw. If a helix is translated (not rotated) through a plane normal to the direction of motion, a rotating point of contact is made by the intersection of these shapes. An arrow on the polarization ellipse can be used to denote the direction of this rotating intersection, as shown in Figure 1. Convention is to show the ellipse from the perspective of the detector (looking back at the source).

Figure 1: A right-handed polarization ellipse as viewed from the perspective of the detector



1.1.Polarization Optics

Polarization optics use the anisotropy in certain materials to affect the transmitted or reflected intensity and/or state of polarization. These materials are generally described by their eigenaxis or eigenaxes. For example, a standard linear retarder (waveplate) can consist of a polymer, stretched such that the polymer chains align in a single direction. The component of light that is polarized in the same direction as the polymer chains is slowed more than the component of light that is polarized perpendicular to the polymer chains. These axes are known as the slow axis and the fast axis, respectively. The amount that one component of light is delayed more than the other, is known as retardance and is usually expressed in fractions of a wave at the wavelength of interest. Quarter-wave retarders are frequently used to change linear polarization into circular polarization, while half-wave retarders are frequently used to create a polarization state, which is orthogonal to the input state.

Another commonly used polarization optic is the linear polarizer. A standard linear (dichroic) polarizer can consist of a polymer, which contains dye molecules aligned to point in the same direction. In this case the component of light polarized parallel to the dye molecules is mostly absorbed, while the component of light polarized perpendicular to the dye molecules is mostly transmitted. These two axes are known as the absorption axis and the transmission (or polarization) axis, respectively. An ideal polarizer has no absorption along its transmission axis and no transmission along its absorption axis. However, since ideal polarizers do not exist, a commonly used figure of merit for polarizers is the extinction ratio. The extinction ratio is defined as the minimum intensity (T_{90}) divided by the maximum intensity (T_0) of an unpolarized (monochromatic) beam, transmitted through two identical polarizers. T_{90} refers to two polarizers oriented so that their transmission axes are at 90˚ to one another, while T_0 refers to their transmission axes being at 0˚ to one another.

1.2.Polarization Alignments

Azimuthal alignment of the eigenaxes in polarization optics is an important part of working with polarization optics. The generation and measurement of polarization states with small uncertainties require both high quality optics and accurate alignment. A basic alignment consists of aligning a polarizer transmission axis with respect to a datum plane. Once this has been done, it allows the user to align optics mechanically instead of optically. This can be a real time saver if you want to make a modular polarization system, where different types of elements can quickly be assembled. A common alignment consists of aligning one polarizer transmission axis with respect to another polarizer transmission axis. This configuration is frequently used to attenuate light in an optical system. The equation governing this attenuation is the Law of Malus, and is used extensively for aligning polarization optics. Equation (1) describes the transmission ratio of a normally incident, unpolarized beam passing through two ideal polarizers,

$$\frac{T(\theta)}{T_0} = \cos^2\theta \tag{1}$$

where θ is the angle between the transmission axes of the two polarizers, known as the angle of crossing[1]. Another frequent alignment consists of aligning a retarder to a polarizer. This is done most often using a quarter-wave retarder for making circular polarization. To do this the retarder must be positioned at an angle of 45˚ to the transmission axis of the polarizer. This combination creates a circular polarizer. Circular polarizers are useful as isolators to suppress back-reflections and the amount of suppression is a function of the alignment and retardance accuracies. Another alignment situation consists of aligning two (or more) retarders. This is done generally to obtain improved performance over a single retarder. With the correct design, a retarder stack can improve achromaticity, athermality, and/or obliquity effects[2]. The angle of alignment between retarders depends on the design, but frequently they are aligned such that the fast axis of one is either parallel or perpendicular to the fast axis of the other. There are many other types of alignments, but this paper will only focus on a few.

1.3. Alignment Tooling

Several off-the-shelf tools exist for performing such alignments. Polarimeters are excellent tools for aligning and understanding polarization states[3]. Typically they can be used at multiple wavelengths and provide good accuracy. However, automatic polarimeters are complex devices and range in cost from about $8,000 to $50,000 for complete systems. Polarimeters are designed to measure much more information than is required for alignment. Simpler devices consisting of one or more rotating mounts will generally suffice for alignment purposes. Automatic rotation stages having high resolution and supporting equipment are available for $8,000 and higher. Good manual rotation stages have micrometer control over resolution at a nice price of $300 - $500. However, because they require the user to read a vernier, repeatability is limited when the micrometer does not provide sufficient throw. Repeatability is essential for accurate alignments of polarization optics.

A solution to this problem is a "rotatable" mount, which allows for positioning at discrete angles, whose price is comparable to that of a good manual rotation stage. A suitable "rotatable" mount could be a rotation stage with detents or a housing with multiple mounting facets. The latter type will be used for the examples in this paper and a model is shown in Figure 2. The mount should be precision machined, such that machining errors between facets are minimized. The facets correspond to angles of 0˚, +90˚, and +45˚. A fine adjustment screw in the mount allows for the azimuth of an optic to be changed relative to the facets. The "rotatable" mount should also be capable of revolving around the normal of the datum plane. This allows +45˚ and -45˚ to be obtained. Generally a flat on the mount is butted against a flat datum plane, but kinematic mounting can provide better repeatability. The mount shown in Figure 2 is quasi-kinematic, since the mounting pins contact a surface with two lines instead of three points. A set of two such mounts, one holding a polarizer and the other holding a half-wave retarder, which are aligned to the same reference plane, can be used to do the aforementioned polarization alignments.

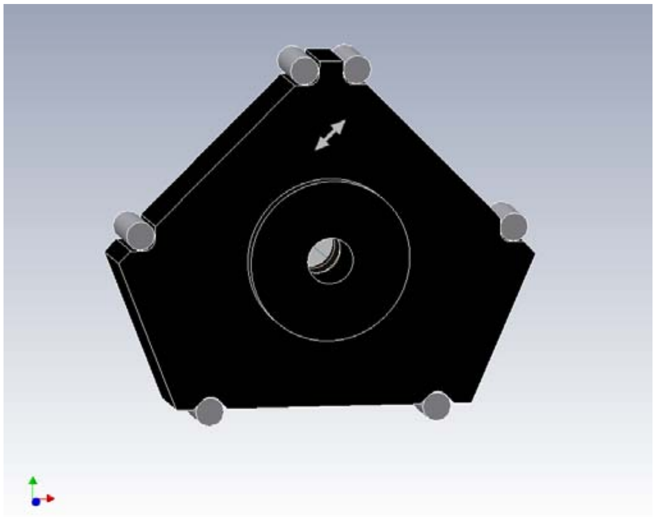


Figure 2: A quasi-kinematic “rotatable” mount

The “rotatable” mount can be useful for aligning polarization optics on an optics bench or elsewhere. The polarization optics to-be-aligned can be in conventional rotation stages so that fine positioning can be performed. After all polarization optics have been positioned, the “rotatable” mounts can be easily removed from the system, so that they do not interfere with the experimental setup.

2. METHODOLOGY

2.1.A closer look at the Law of Malus and the method of swings

The simplest way to align two polarizers with respect to one another is to make use of the Law of Malus. If we find a minimum of transmission or null, we know that the transmission axes are at 90˚ to one another. Consider the case shown in Figure 3, where the polarizer closest to the detector (analyzer) is rotated. The transmission curves plotted as a function of the angle of crossing, θ, are shown in Figure 4. We notice from this plot that the slope becomes zero when the two polarizers are at ± 90˚ to one another. This reduces the accuracy of alignment since the sensitivity to angular change (dT/dθ) is very small. To improve the accuracy of the alignment, we can rotate the analyzer by Δθ to obtain transmission measurements at θ = 90˚ + Δθ, ($T_{+\Delta\theta}$), and θ = 90˚ - Δθ, ($T_{-\Delta\theta}$). We know that when these two transmission measurements are equal, the null lies halfway between these two angles. If the two measurements are not equal, then the polarizer must be rotated slightly and the measurement repeated. This method of symmeterizing is known as the method of swings[4]. It is possible to collect additional intensity data between –Δθ and +Δθ and perform a curve fit to find the null. For this paper, that solution is not considered economical, since it would require a motorized rotation stage and data acquisition system, to be performed quickly. Figure 4 reveals that the slope is a maximum when the polarizers are at ±45˚ or ±135˚ to one another. Therefore, to achieve the greatest angular sensitivity, the analyzer should be toggled using Δθ = 45˚, i.e. between 45˚ and 135˚, in order to align a polarizer at 0˚. A variation of the method of swings is to use the configuration shown in Figure 5, which introduces a half-wave retarder between the polarizer and analyzer. For this method, the half-wave retarder is toggled between the angles of 22.5˚ and 67.5˚. Figure 6 shows the transmission curves for these two cases as the analyzer is rotated. We see that the curves are shifted by ±45˚ from the curve in Figure 4 and that the points of greatest angular sensitivity are coincident at 0˚, ±90˚, and ±180˚. This method can be useful for certain alignment situations and mitigating detector polarization sensitivity (discussed later).

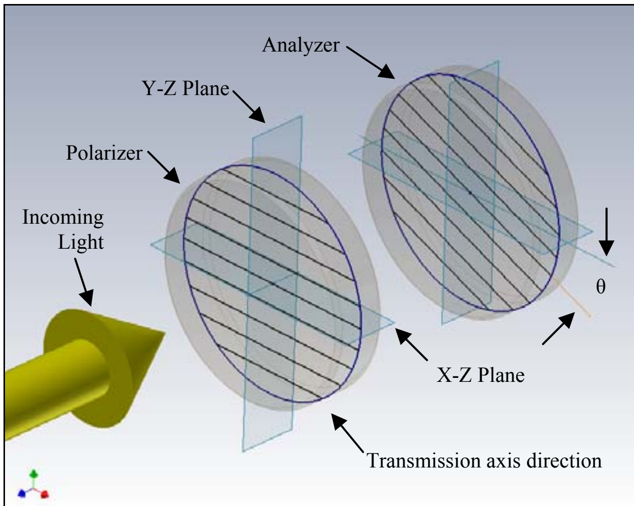


Figure 3: Polarizers at an arbitrary angle of crossing

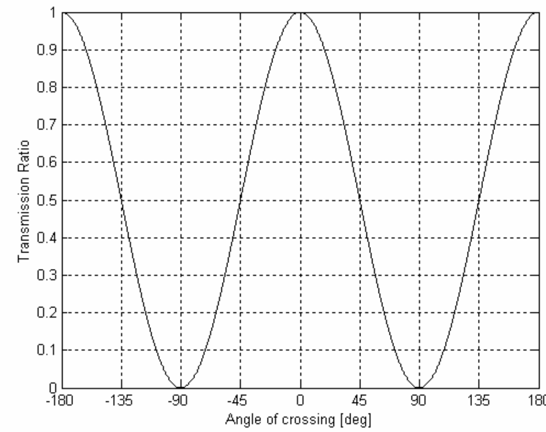


Figure 4: Transmission ratio, $T(\theta)/T_0$ vs. angle of crossing, θ

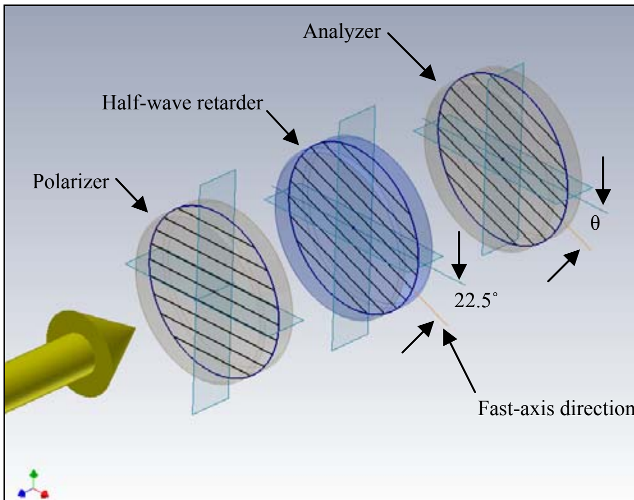


Figure 5: Polarizer-Retarder-Polarizer

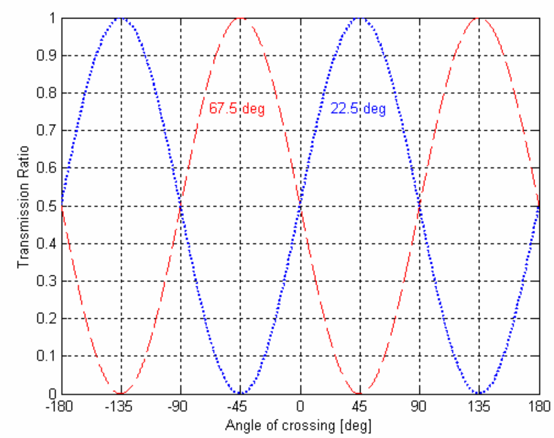


Figure 6: Transmission ratio, $T(\theta)/T_0$ vs. angle of crossing, θ

2.2.The Poincaré Sphere

The Poincaré Sphere will be used in this paper to visualize how azimuthal alignments work. A convenient way to visualize polarization states and to predict the effects of polarization optics is to use the Poincaré Sphere. Shurcliff gives an excellent description of the Poincaré Sphere and its uses[1], but a brief summary follows. A picture of the sphere illustrating several states is shown in Figure 7. Each polarization state (linear, elliptical, or circular) may be represented by a point on the surface of a unit radius sphere and defined by its latitude and longitude. Some important rules of the sphere are listed below.

Rule 1. The polarization states lying on the equatorial plane are linear.

Rule 2. The polarization states lying on the poles are circular.
Rule 3. All the other points on the sphere represent elliptical polarization states.
Rule 4. Polarization states on the sphere are depicted from the perspective of a detector and *not* a source.
Rule 5. Each polarization state on the surface is represented as viewed from an extended radius.
Rule 6. Diametrically opposing points on the sphere represent orthogonal polarization states.
Rule 7. Horizontally polarized light has the point of 0˚ longitude and 0˚ latitude.
Rule 8. The southern hemisphere represents right-handed polarizations, while the northern hemisphere represents left-handed polarizations.
Rule 9. The longitude of a polarization state represents twice the angle of the major axis, α, of the polarization ellipse (with respect to horizontal) as follows: longitude = 2· α
Rule 10. The latitude of a polarization state represents the ellipticity, ε, of the polarization ellipse as follows:
latitude = 2·arctan(ε).

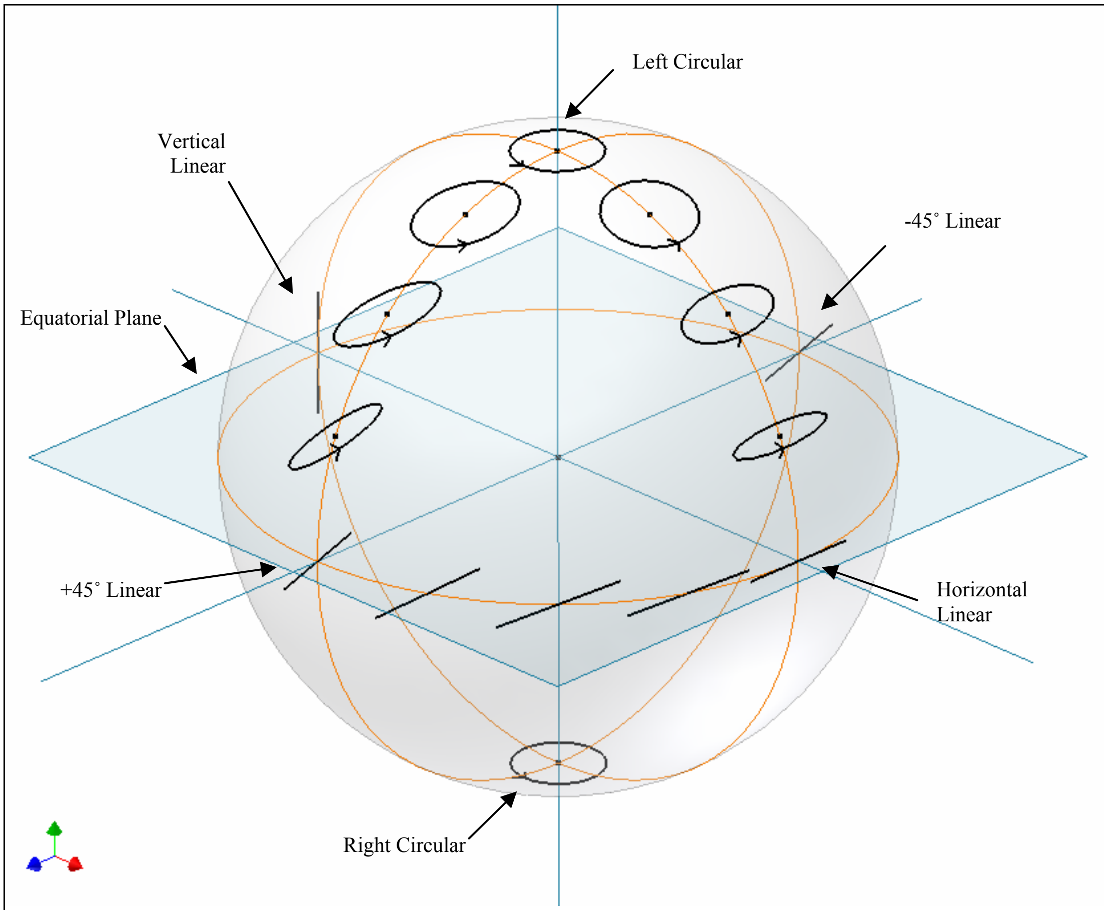


Figure 7: Poincaré Sphere

The Poincaré Sphere is extremely useful for determining the effects of any retarder on a polarization state. The recipe for use with linear retarders is listed below and illustrated in Figure 8.

Step 1. Find point A on the sphere, which corresponds to the initial polarization state.
Step 2. Find point B on the equator of the sphere, which corresponds to the angle of the *fast-axis* of the linear retarder. Remember that this is from the perspective of the detector and *not* the source.
Step 3. Draw a line between point B and the center of the sphere, which will represent the axis of rotation.
Step 4. Rotate point A around the axis of rotation in a clockwise fashion (as viewed from an extended radius on the axis of rotation).
Step 5. The angle of rotation is equal to the retardance of the retarder expressed in angular units, i.e. quarter-wave retarder causes a 90˚ rotation. The final state is called point C.

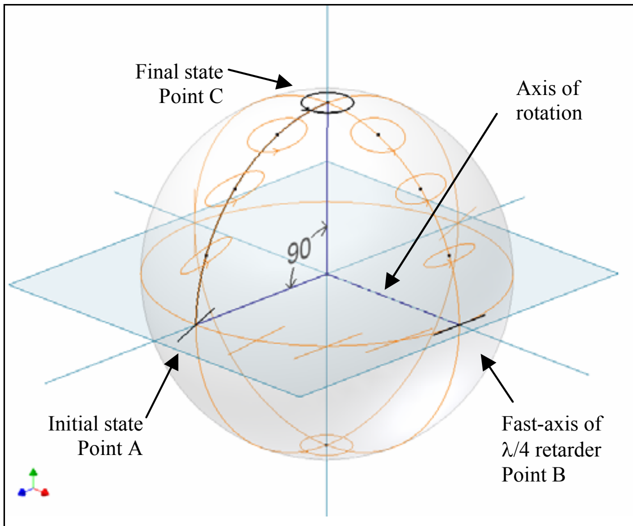


Figure 8: A visualization of changing +45 linear to left circular via □/4 retarder

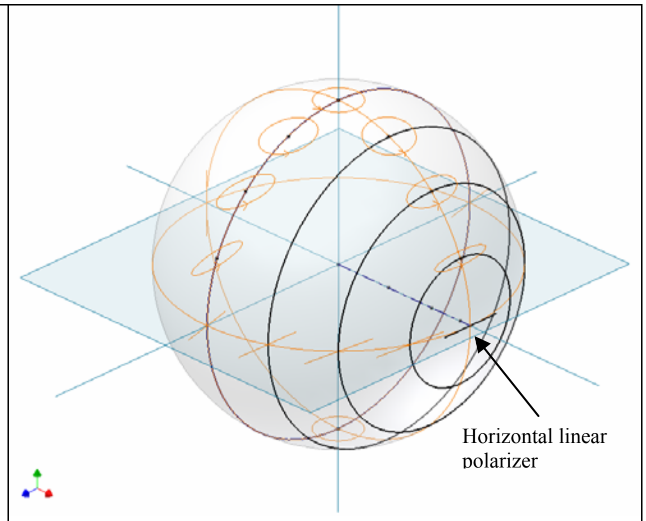


Figure 9: A visualization of iso-intensity lines about horizontal linear polarizer

Some observations follow about using this method to predict changes to the polarization state after a linear retarder.

Observation 1. The only way to go from a linear state to a circular state with a single retarder is to use quarter-wave retarder.
Observation 2. A half-wave retarder will output a linear state, regardless of the orientation of the fast-axis, if the input is a linear state.
Observation 3. A full-wave retarder causes a rotation of 360˚, which brings about no change in polarization.
Observation 4. Since a retarder only changes the phase between an x and y component of polarization, all the points on a circle centered around the axis of rotation will have the same relative x and y intensity components. A consequence of this is that an analyzer aligned with the fast axis of the retarder will measure the same transmission intensity, regardless of the retardance.

The usefulness of Observation 4 is not completely clear yet, so it will be explained further and is illustrated in Figure 9. Say there is a polarizer with its transmission axis at 0˚ and an incident beam of unit intensity light. For the first case, let the incident beam be linearly polarized at +45˚ (remember this is +90˚ longitude on the Poincaré Sphere). Using the Law of Malus, the amount of light transmitted is 50%. For the second case, let the incident beam be linearly polarized at -45˚. The amount of light transmitted is again 50%. For the third case, let the incident beam be circularly polarized. Again the amount of light transmitted is 50%. This leads to a more generalized Law of Malus, which is valid for an arbitrary polarization state, which passes through a polarizer. The equation is the same, but the angle θ is now defined as *half* the angle between the line connecting the center of the Poincaré Sphere and the incident polarization state and the line connecting the center of the Poincaré Sphere and the polarizer transmission axis.

Since alignment techniques will be described using the Poincaré Sphere, it is important to have a quick method for determining if two polarization states result in the same intensity measurement. Therefore, it is useful to remember that all the points of a circle on the Poincaré Sphere whose center lies on a line connecting the transmission axis of a polarizer to the center of the sphere will yield the same transmitted intensity.

2.3. Aligning a polarizer and a half-wave retarder to a datum plane

Aligning a polarizer and half-wave retarder to a mechanical datum plane requires three steps. The first step is to align a polarizer in a "rotatable" mount, such that its transmission axis is parallel (or perpendicular) to the datum plane. This is shown in Figure 10. An intensity measurement is made using an analyzer at roughly -45˚ to the polarizer, and the beam going through side A of the polarizer first. The polarizer is then revolved 180˚ around the normal of the datum plane, such that the beam now passes through side B first. These two measurements are plotted on the Poincaré Sphere from a southern-pole view in Figure 11. It is apparent that if the transmission axis of the polarizer is aligned parallel (or perpendicular) to the datum plane, then the intensity of the beam will not differ depending on which side is forward. The polarizer is now aligned parallel to the datum plane, which we shall refer to as 0˚ of azimuth. Since the "rotatable" mount has been precision machined to have multiple azimuthal alignments, all are now relative to the datum plane.

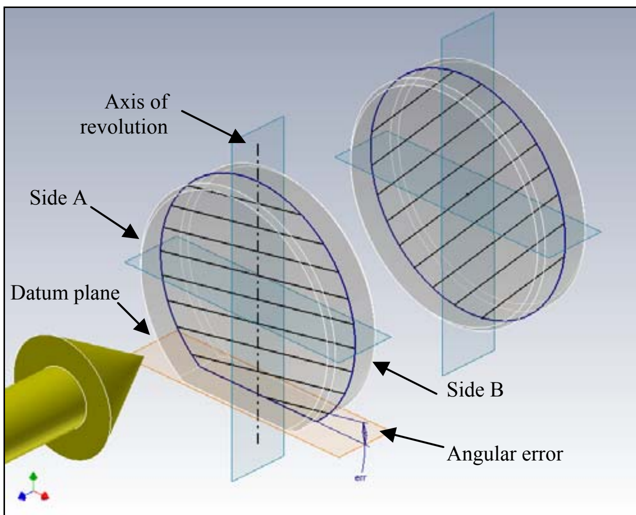


Figure 10: Azimuthal misalignment of a polarizer measured by revolving side A and side B

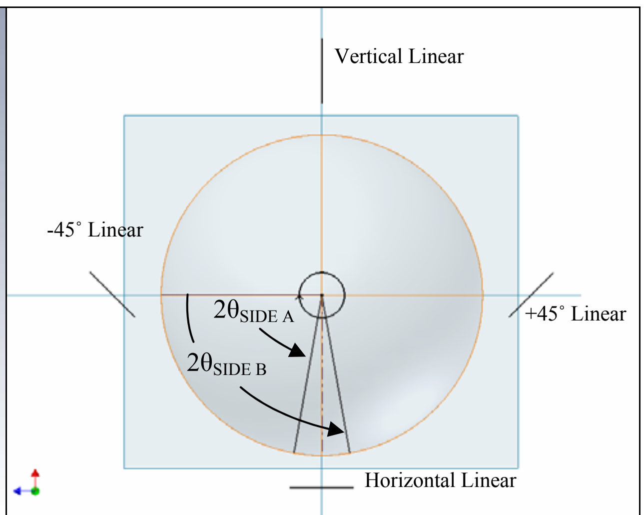


Figure 11: Southern-pole perspective of angle of crossing when side A is forward vs. when side B is forward

The second step requires building another mounted polarizer as described in the first step. This second polarizer will serve as an analyzer in the third step. This step is only required for aligning the half-wave retarder described in the third step.

The third step is to mount a half-wave retarder in a "rotatable" mount. The mount should be able to toggle easily by 45˚. The configuration shown in Figure 12 uses the polarizer and analyzer from the first and second steps. The analyzer and polarizer transmission axes should both be at 0˚. With the half-wave retarder between them and roughly set to toggle between fast-axis positions of 22.5˚ and 67.5˚, begin the method of swings. This is represented on the Poincaré Sphere in Figure 13**,** where the initial state is the polarization state after the polarizer and the final state is the polarization state before the analyzer. When the polarization states produced from each toggle position both lie on a circle centered on the axis connecting the transmission axis of the analyzer to the center of the Poincaré Sphere (as described in Observation 4), the transmitted intensities are equal, and the half-wave retarder is aligned.

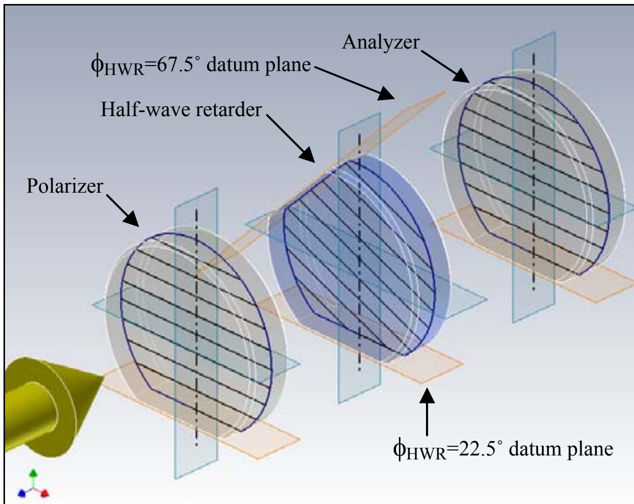


Figure 12: Configuration for aligning a half-wave retarder

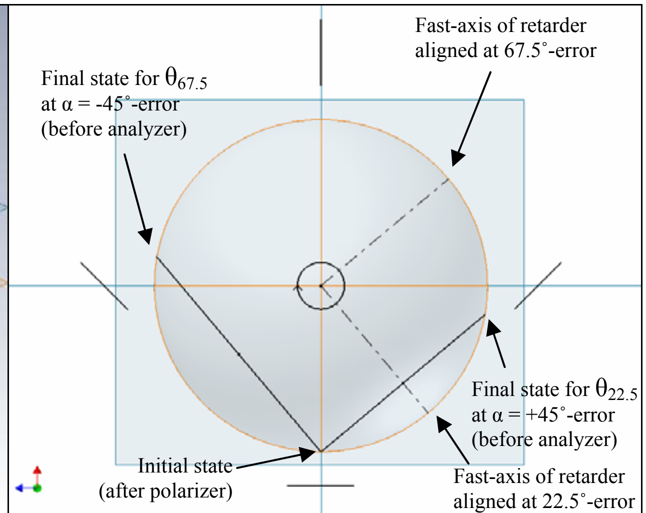


Figure 13: Visualization of a misaligned half-wave retarder from southern-pole perspective

2.4. Aligning one polarizer with respect to another

To align a polarizer at an arbitrary azimuth to either a mechanical datum or another polarizer requires the tooling created in the previous alignment method. For this example, let's say we want to align a polarizer at 10˚ from parallel, (ϕ_P = 10˚), with respect to a horizontal analyzer (ϕ_A = 0˚). Figure 14 shows the configuration. The effects of the half-wave retarder toggled between 22.5˚ and 67.5˚ are shown on the Poincaré Sphere in Figure 15. We notice that the two states exiting the half-wave retarder are orthogonal polarizations. Because of the orthogonality, we can solve for the azimuth of the polarizer by using Equation (1) to form a ratio for the case where the fast-axis of the half-wave retarder is positioned at ϕ_{HWR} = 67.5˚, $\theta_{67.5}$, and the case where the retarder is positioned at ϕ_{HWR} = 22.5˚, $\theta_{22.5}$. In this case θ represents the angle of the polarization state coming into the analyzer (and exiting the half-wave retarder), which is essentially the same as the angle of crossing. Equation (2) shows the ratio while Equation (3) shows its solution for the angle of the transmission axis of the polarizer, ϕ_P.

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$$\frac{T(\theta_{67.5})}{T(\theta_{22.5})} = \frac{\cos^2(\theta_{67.5})}{\cos^2(\theta_{22.5})} \tag{2}$$

$$\phi_P = 45° - \arctan\sqrt{\frac{T(\theta_{67.5})}{T(\theta_{22.5})}} \tag{3}$$

For some cases it may be necessary to position the analyzer at 45˚ instead of 0˚ to attain high angular sensitivity. This is true when the polarizer transmission axis is close to 45˚ azimuth. Once we calculate the intensity ratio required for ϕ_P = 10˚, using Equation (3), we can keep adjusting the polarizer azimuth until the measured intensity ratio equals the calculated.

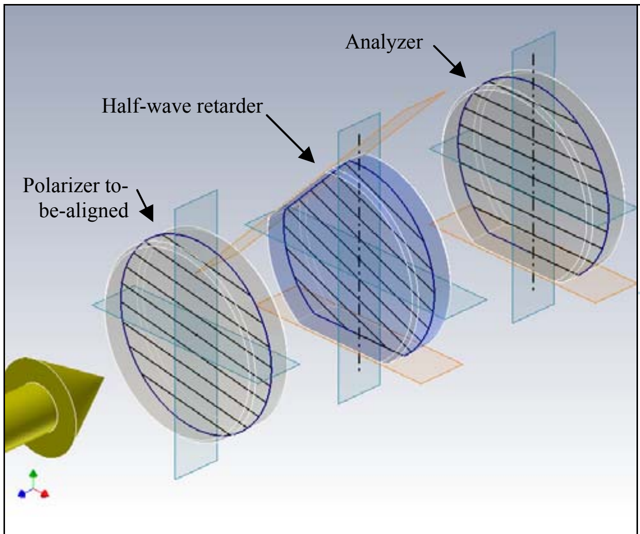

Figure 14: Configuration for aligning a polarizer at an arbitrary azimuth

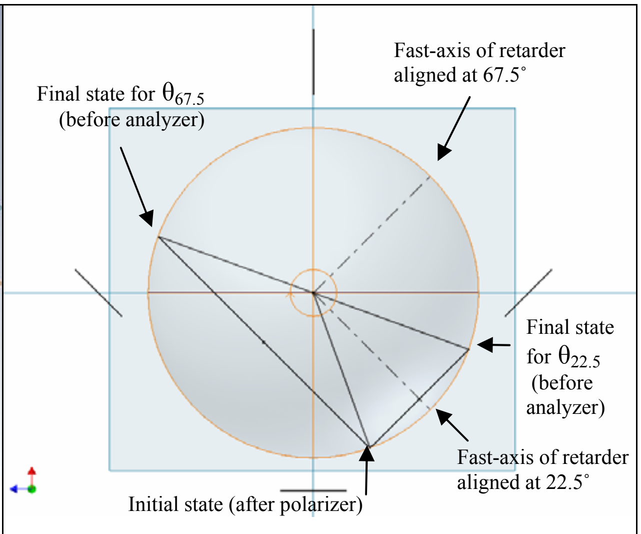

Figure 15: Visualization of the alignment of a polarizer to an arbitrary azimuth from southern-pole perspective

2.5. Aligning a quarter waveplate at 45˚ to a polarizer

For simplicity, let's consider the case where the polarizer is aligned at 0˚ and the quarter-wave retarder is aligned at 45˚. The first step in creating a circular polarizer is to align a polarizer. The configuration to do this is shown in Figure 14. The analyzer is set to 0˚ and the half-wave retarder is toggled between 22.5˚ and 67.5˚. Using the method of swings, the polarizer is aligned to 0˚ when $T(\theta_{67.5}) = T(\theta_{22.5})$.

The second step is to align the quarter-wave retarder. If the retarder has some retardance error and is not exactly quarter wave, the output light will be elliptical no matter how good the alignment. However, good alignment is still essential, since the ellipticity will be closest to unity (purely circular), when the major axis of the output ellipse is aligned parallel or perpendicular to the input linear state. The alignment configuration is shown in Figure 16. Again the analyzer is set to 0˚ and the half-wave retarder is toggled between 22.5˚ and 67.5˚. The quarter-wave retarder is aligned to 45˚ when $T(\theta_{67.5}) = T(\theta_{22.5})$, and this is shown on the Poincaré Sphere in Figure 17.

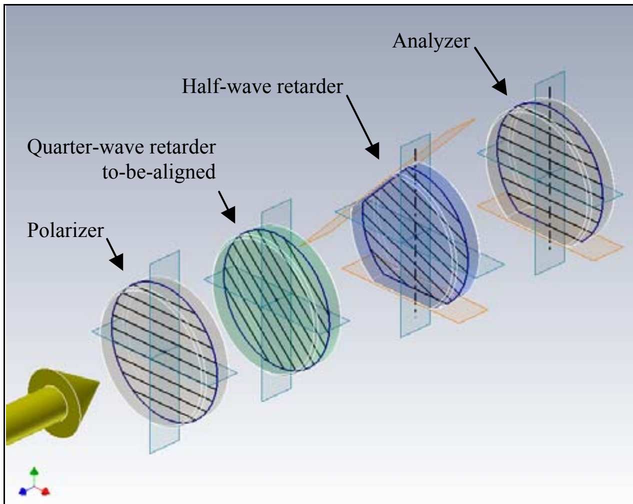

Figure 16: Configuration for aligning a quarter-wave retarder at 45˚ to a polarizer

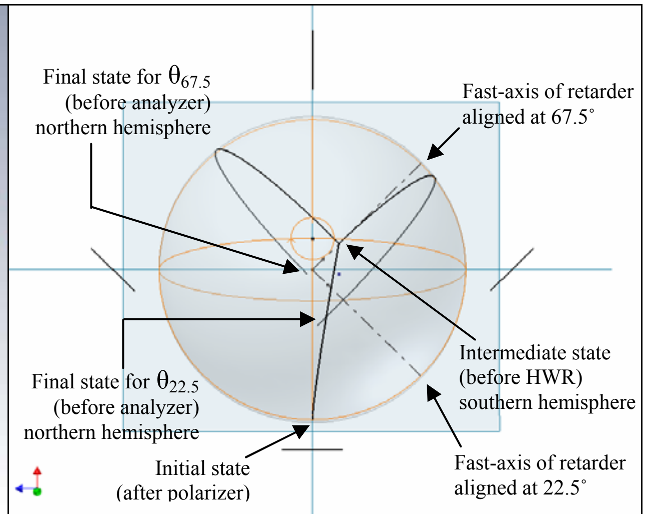

Figure 17: Visualization of a misaligned quarter-wave retarder from southern-pole perspective

3. DISCUSSION OF ERRORS

3.1.Errors in polarization optics

Nonideal polarizers suffer from absorption along the transmission axis and transmission along the absorption axis, and thus have a non-zero extinction ratio (ER). This changes the Law of the Malus as shown in Equation (1) into Equation (4) shown below[1].

$$\frac{T(\theta)}{T_0} = ER + (1 - ER)\cos^2\theta \tag{4}$$

The effect of a large ER is to reduce the modulation depth of the curve shown in Figure 4, thus reducing the angular sensitivity of the alignment method. Extinction ratios are typically between 10^{-3} and 10^{-4} for dichroic sheet polarizers. The smaller the ER, the more closely a real polarizer resembles an ideal polarizer.

Polarizers usually have some retardance[5]. Since sheet (dichroic) polarizers are constructed in a similar method to retarders, it is no surprise that this occurs. In this case, there is an optical path length difference between light transmitted along the transmission axis and light transmitted along the absorption axis. Thus the output state of polarization will be very dependent on the input state of polarization. For this reason, it is extremely important to use a polarizer with a small ER.

The accepted state and transmitted state of a polarizer can be different[5]. This is easily understood if one considers putting two polarizers together with a slight azimuthal misalignment. The upstream polarizer may be oriented at 0˚, while the downstream is oriented at 1˚. This will cause all kinds of problems, when revolving such a polarizer to align to a datum plane. This is generally not a problem with dichroic polarizers made of a single sheet, but can be a problem for birefringent prism-type polarizers.

Retarders may have incorrect retardance. The retardance of a waveplate can change with wavelength, angle of incidence, and environmental conditions. This paper has assumed that the wavelength is stable, the angle of incidence is always normal, and that environmental conditions are constant. Regardless of this, there is always retardance uncertainty during the manufacturing of a retarder. It is for this reason that the toggling angles of the fast axis of the half-wave retarder were chosen to be 22.5˚ and 67.5˚, instead of something like +22.5˚ and –22.5˚, when the transmission axis of the analyzer is horizontal. When the input state is purely linear it will not matter, but when the input state is not linear, it is important that fast-axes of the retarder not be symmetrical about the analyzer. This effect is shown on the Poincaré Sphere in Figure 18 and Figure 19, where the half-wave retarder is slightly less than half wave. In order to obtain equal transmission intensities through a horizontal analyzer, the 22.5˚ and 67.5˚ cases must be used for alignment, thus compensating for retardance errors.

Polarization optics may not be homogeneous. If a polarizer is homogenous, either face may be used as the first or second surface without changing the output polarization state. If a linear polarizer is not homogenous, then there will be a face, denoted as the *prime face*, which will produce the greatest degree of polarization[1]. For polarizers, the prime face should be positioned to be the exiting face and for analyzers the prime face should be positioned to be the entering face. Sheet polarizers (and retarders), which are laminated in glass, can become inhomogeneous if the glass or glue layers have residual retardance. For this reason it is very important to always use high quality glass for laminating polarization optics and to use low stress adhesives for laminating and mounting the optic into a housing.

Polarization optics may have axis wander. This means that the direction of the eigenaxes change as a function of position on the optic. This is generally the result of inadequate manufacturing equipment and/or poor uniformity of the starting material. This effect may be mitigated by positioning the optic in the same beam location, so that errors tend to average out.

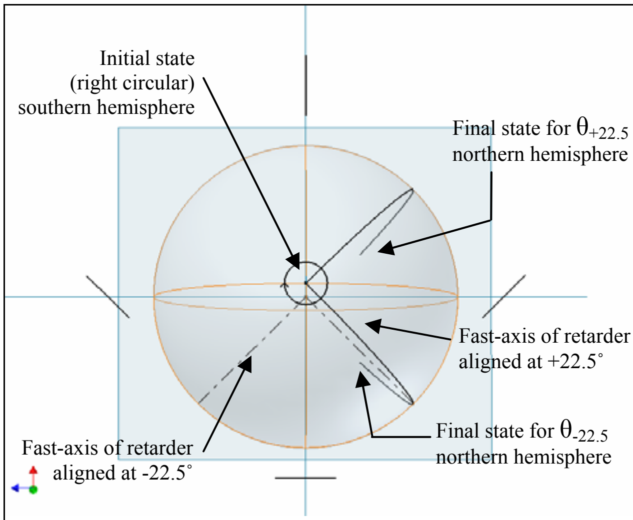

Figure 18: Effect of a 0.4 wave retarder toggled between +22.5˚ and -22.5˚ from southern-pole perspective

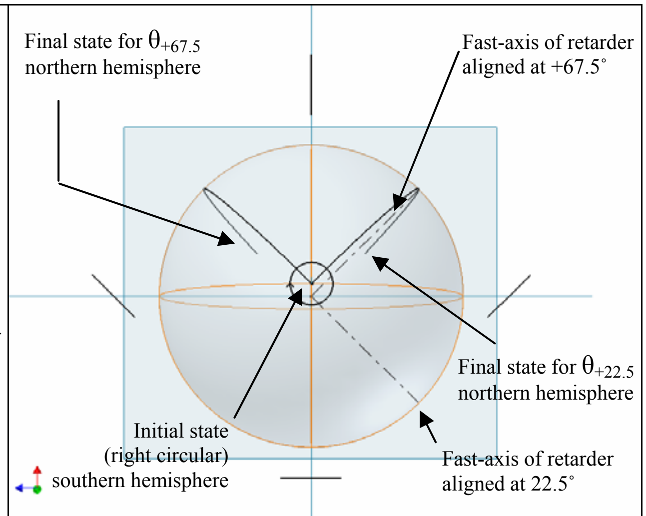

Figure 19: Effect of 0.4 wave retarder toggled between +22.5˚ and +67.5˚ from southern-pole perspective

Polarization optics may depolarize the light they transmit. Causes of this include surface roughness, scratches, digs, or contamination in or on the optic. Significant scattered light will have detrimental effects on the alignment process. The remedy for this is to use well-polished optics having high quality glass and coatings, free of blemishes, and painstakingly cleaned.

Multiple reflections in polarization optics will cause problems. For example, a beam that has done 3 passes through a retarder has been retarded more than a beam that has done only a single pass. This translates to a net retardance error. Another problem occurs when a coherent beam is used, and the measurement of the transmission includes etaloning effects. To mitigate this problem, all retarders and polarizers should have anti-reflection coatings.

More defects in polarization elements are possible, but these are some of the most common ones, which can affect the alignment techniques described in this paper.

3.2.Errors in supporting equipment

Detectors have polarization dependent sensitivities. This means that a detector will output a different signal, when measuring a beam of equal intensity but a different polarization state. This error has been reported by a manufacturer[6] to be around 0.2% - 0.6%. This can be a major source of error for alignments.

It is for this reason that this paper focused on performing alignments using a toggled half-wave retarder and a fixed analyzer, instead of a toggled analyzer (and no half-wave retarder). Advantages of using a toggled analyzer include increased achromaticity and decreased uncertainties from the incorporation of the half-wave retarder. The disadvantages are that (1) the output beam must be depolarized before hitting the detector and (2) there is less flexibility for alignment setups. The first disadvantage can be mitigated by using a suitable depolarizer. Integrating spheres work well, but attenuate the signal substantially and are expensive. Crystal wedge depolarizers work by scrambling the polarization state across the cross-section of the beam, so that different points of the detector see different polarizations. Thus the net effect is a spatial averaging of different polarizations. However, the crystal wedge for use with monochromatic beams also contains an eigenaxis, which must be aligned with respect to the incoming state. This paper has focused on using the alignment technique where the polarizer to-be-aligned is upstream of the optics in the "rotatable" mounts, but it is entirely possible to use a configuration where the polarizer to-be-aligned is downstream, thus becoming the analyzer to-be-aligned. Since sources generally have at least some partial polarization, extra care must be taken during the measurement to get accurate results. If the polarizer (in the "rotatable" mount) is toggled upstream of the analyzer to-be-aligned, the output intensity (from the polarizer) for the two toggled positions will differ depending on the input polarization state. Thus alignment using the method of swings will not be possible, since intensity differences are not only a function of analyzer misalignment, but also polarizer azimuth. If however, the half-wave retarder is inserted between the polarizer and analyzer, the retarder may be toggled without affecting the intensity output from the polarizer, and alignment can proceed as described in this paper.

Detectors have spatial dependence sensitivities. Uniformity of a detector is not perfect, and if the beam is displaced when the half-wave retarder is toggled, the detector may report that the beam intensity has changed when it has not. For these reasons it is important to align the half-wave retarder normal to the beam, and that the retarder itself has a very small wedge. Keeping the detector as close to the retarder as possible will also help mitigate the wedge problem.

Sources are not stable. The intensity emanating from a source will change over time and environmental conditions. Instabilities in polarization state will also cause intensity changes after passing through a polarizer. To reduce this effect, sources should be intensity stabilized and polarization stabilized. Additionally, vibrations must be well controlled, so that filaments do not shake and fibers do not bend.

Mounts have angular error and mating precision is never perfect. Mounts should be precision machined using a high-quality CNC machine and rigid tooling. Mating surfaces should be ground or polished, to reduce friction and increase precision. Mating pieces should always be mated carefully and should be hardened to reduce scratching and deformation. Mating surfaces should be cleaned thoroughly so that contamination does not reduce precision.

4. CONCLUSIONS

The method of swings is very useful for aligning optics and the Poincaré Sphere is a useful tool for quickly visualizing the alignment process. Alignments using this method can be done economically and quickly with a relatively small time investment for setup. An optic mounted in a "rotatable" mount will speed up the alignment, while enhancing the accuracy of the alignment. Alignments using a toggled half-wave retarder allow the method of swings to be employed in a very flexible manner. Finally, the importance of using high-quality optics and equipment was discussed.

5. REFERENCES

1. W. Shurcliff, *Polarized Light*, Harvard University Press, Cambridge, 1966.
2. S. Guimond, D. Elmore, "Designing effective crystal waveplates requires understanding the engineering tradeoffs", *OE Magazine*, **V4**, N5, P26, 2004.
3. T. Drouillard II, P. Searcy, "Knowing the math aids measurements of polarization", *Laser Focus World*, **V40**, N1, P123, 2004.
4. R.M.A. Azzam, N.M. Bashara, *Ellipsometry and Polarized Light*, P403, Elsevier Science, Amsterdam, 1987.
5. R. Chipman, *Handbook of Optics*, McGraw-Hill, New York, Chapter 22, Volume II, Second Edition, 2001.
6. Agilent Technical Specifications, Agilent Power Sensor Modules, Agilent Technologies, 2004.